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MECHANICAL AND THERMOMECHANICAL PROPERTIES OF CARBON FIBRE REINFORCED THERMOPLASTIC COMPOSITE FABRICATED USING FUSED DEPOSITION MODELLING (FDM) METHOD: A REVIEW

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ABSTRACT

Fused deposition modelling (FDM) is widely used method to fabricate thermoplastic parts, which are mainly used as rapid prototypes for functional testing with advantages of minimal wastage, and ease of material change. Due to the intrinsically limited mechanical properties of pure thermoplastic materials, there is a critical need to improve mechanical properties for FDM-fabricated pure thermoplastic parts. One of the possible methods is adding reinforced materials (such as carbon fibers) into plastic materials to form thermoplastic matrix carbon fiber reinforced plastic (CFRP) composites those could be directly used in the actual application areas, such as aerospace, automotive, and wind energy. The current study is focused to take a look of the work done in the area of 3D printing with thermoplastic material and carbon fiber reinforced thermoplastic material. The study is attempting to take an overview of reinforcement of different materials into thermoplastic in different ways. The effect of reinforcement of carbon fiber into thermoplastic can be studied by using different mechanical and thermo mechanical tests. The effects of different fiber orientation on mechanical properties, effect on infill speed, and nozzle temperature and layer thickness on tensile properties are also studied. This paper reviews work related to investigation of mechanical and thermo mechanical properties of carbon fibre reinforced thermoplastic composite fabricated using fused deposition modelling (FDM).

KEYWORDS: 3 D Printing, Additive Manufacturing & Polylactic Acid

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Original Article

INTRODUCTION

Three-dimensional (3D) printing or additive manufacturing enables the fabrication of near net shaped complex 3D parts without expensive molds or tools in short periods of time, based on 3D computer-aided design (CAD) data. 3D printing is expected to revolutionize the manufacturing of components. While several 3D printing systems available are printing based on fused-deposition modelling (FDM) using thermoplastics is particularly widespread, because of the simplicity and potential applicability of the method [1].

3D printers that run on FDM technology build parts layer-by-layer from the bottom up by heating and extruding thermoplastic filament. FDM usually deals with thermoplastics or composite materials. The nozzle follows computer controlled paths as in computer numerical control machines (CNCs), while extruding the material to draw layers on top of each other to create the part as shown in Figure 1.

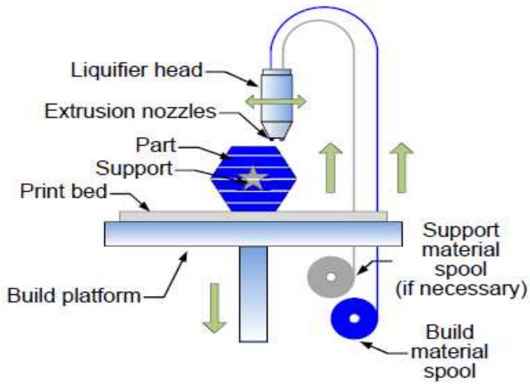

Figure 1: Schematic of FDM Process [2]

The FDM process belongs to the 3D printing prototyping processes. Material spool pass into the small diameter of nozzle with tension. The liquefier head liquefies the material and is passed to the extrusion nozzle. Extrusion nozzle print the material on the heated bed with layer by layer from the bottom up. The build platform moves in upward and downward direction and nozzle movement is in 3 dimensional pattern. The continuous reinforcement of any other material into thermoplastic can be done by adding another spool and pass it into the nozzle for printing [2].

LITERATURE REVIEW

Li et.al [3] manufactured continuous carbon fiber reinforced polylactic acid composite by using rapid prototyping approach of 3D printing. They investigated the mechanical strength and thermodynamic properties, which were measured by using the electronic testing machine and dynamic mechanical analyzer (DMA). The design of nozzle and path control method was developed in such a way that it can satisfy the demands of continuous carbon fibre printing. They concluded that tensile strength and flexural strength of modified carbon fibre reinforced composite were 13.8% and 164% higher than original carbon fibre reinforced sample. The storage modulus of modified carbon fibre reinforced sample is higher than the PLA and original fibre reinforced sample for about 166% and 351% respectively. The scanning electron microscope (SEM) images result indicated that preferable bonding interfaces were achieved of modified carbon fibre reinforced composite.

Dickson et.al[3] studied the performance of continuous reinforcement of carbon, Kevlar and glass fiber into nylon, which are manufactured by using FDM. They investigated the mechanical properties of composite sample in flexural and tension and also considering fiber orientation, fiber type and volume fraction. The results were compared with that of both pure nylon specimen and known material properties. They concluded that reinforcement of carbon fiber into nylon shows higher increase in mechanical strength compared to nylon specimen increment in tensile and flexural test up to 6.3 fold and 5 fold. By comparing all composite samples, it was found that the nylon composite strength in the order of carbon fiber>Glass fiber>Kevlar fiber.

Greeley et.al [5] developed an improved and sustainable feedstock material for fused deposition modelling through reinforcement of polylactic acid with graphene and multi-walled carbon nanotubes. Composite with loading of 0.5, 0.2 and 0.1 wt% of reinforcement were extruded to form a filament feedstock for FDM. They investigated mechanical properties by using tensile and impact testing and fracture surface analyzed by using scanning electron microscope. By using differential scanning calorimetry thermal properties were investigated. They concluded that reinforcement of 0.2%

graphene in polylactic acid increases the mechanical properties by 47% in tensile strength, 17% increase in modules, and 12% increase in energy absorbed upon fracture. The 0.1% loading of multi-walled carbon nanotubes had respective increase in 41%, 16%and 9% with all reinforcement no significant change in thermal properties.

Matsuzaki et.al [6] developed method for the 3D printing of continuous fiber reinforced thermoplastic based on FDM. In this method thermoplastic filament and continuous fiber was separately supplied to the 3D printer for printing through heated nozzle. PLA was used for matrix and carbon fiber or twisted jute yarns of natural fiber were used for reinforcement. During their research they found that carbon fiber reinforced composite shows mechanical properties superior to those of jute reinforced and unreinforced thermoplastic. The tensile modulus and strength of carbon fibre reinforced thermoplastic were 19.5GPa and 185.2MPa respectively. Flexural strength and modulus were 133 MPa and 5.93 GPa respectively for carbon fibre reinforced thermoplastic.

Dong et.al [7] investigated the effect of fibre content (5-30wt%) and fibre treatment on surface morphology, tensile, flexural, thermal and biodegradable properties of polylactic acid reinforced with coir fibre bio composites were evaluated via scanning electron microscopy (SEM),mechanical testing, differential scanning calorimetry, thermogravimetric analysis (TGA) and soil burial method. During his research the result is 20% treated coir fibre were to achieve optimum tensile and flexural strength of biocomposites. Regardless of fibre treatment the thermal stability of biocomposite was worsened with increasing fibre content. The biocomposite undergo much faster degradation than PLA. The mechanical properties of alkali treated fibre biocomposite better than those untreated counter parts despite being less than that of PLA in both cases. The soil burial test gave result that good biodegradability has shown in biocomposite, especially to a greater extent for those with fibre treatment.

Chumaevskii et.al[8]investigated mechanical properties of both pure and chopped carbon fibre reinforced polyetherketone sample. Fracture surfaces have been examined using both optical and scanning electron microscopy. During their research result showed that carbon fibre reinforcement of polyetherketone matrix result in considerable improvement of the composite strength. Thus tensile ultimate strength, elasticity modulus and compression strength were increased by a factor of 2.8, 3.5 and 2.9 respectively. High mechanical characteristics achieved using carbon fibre reinforcement was provided by effective retarding the structural defect development. By using chopped fibre instead of continuous ones for reinforcement allows more isotropic mechanical characteristics.

Ning et.al[9] studied FDM of carbon fiber reinforced thermoplastic composite, which was manufactured by adding carbon fiber pellets into ABS material and then extruded the filament. After FDM fabrication they investigated the effect reinforcement into tensile properties and Flexural properties by using varying percentage of carbon fiber. SEM micrograph was carried to find the parts fracture reasons during tensile and flexural test of CFRP composite specimen. They concluded that compared with pure plastic specimen, CFRP composite specimen with 5% wt carbon fibre content had larger flexural stress, flexural modulus, and flexural toughness with an increase of 11.82%, 16.82 and 21.86 respectively. The tensile strength and young's modulus of fabricated specimen with 5wt% or 7.5wt% carbon fibre content could increase 22.5% and 30% respectively. Porosity became severe in the specimen with 10 wt% carbon fibre content.

Wang et.al [10] investigated the effect of fused deposition modelling process parameter on mechanical properties of carbon fibre reinforced plastic composite. In this experiment, carbon fibre composite parts were manufactured by FDM and tensile tests were conducted to obtain tensile properties. The effect of FDM process parameter on tensile properties of

FDM fabricated carbon fibre reinforced plastic composite part was investigated. Material failure modes and reasons were observed by scanning electron microscope of part after tensile testing. They concluded that raster angle [0, 90] exhibited larger tensile strength, young's modulus and yield strength than raster angle [-45, -45]. Infill speed of 25m/s led to largest mean value of tensile properties. Nozzle temperature at 220^0c tensile properties first increases and then decreases. Tensile strength, young's modulus and yield strength had the largest mean values when layer thickness was 0.15mm.

Tekinalp et.al[11] investigated short fiber reinforced acrylonitrile butadiene styrene composite as feed stock for 3D printing in terms of their processibility, mechanical performance and microstructure. Reinforcement of carbon fiber into an ABS matrix with varying weight percentage and these feed stock materials were used to fabricate composite by both FDM and compression moulding processes. They concluded that tensile strength and modulus of 3D printed sample increased 115% and 700% respectively. Fibre was highly oriented in the print direction on 3D printed yielding sample on the other hand lower fibre orientation in the compressive molding process yielding sample. While no visible porosity was observed in CM samples, significant porosity was observed in FDM-printed samples. SEM micrographs show that fibres had pulled out of the matrix, indicating weak interfacial adhesion between the fibres and the matrix.

Hinchcliffe et.al [12] described the effect of initial fibre prestressing on the specific tensile and flexural properties of natural fibre-reinforced polylactic acid (PLA) composite materials. They investigated the effects of fibre type (e.g., jute, flax) matrix cross sectional geometry, number of reinforcement strands, and level of initial fibre prestress on the tensile and flexural strength-to-weight and stiffness-to-weight ratios of PLA matrices. During their research, results show that utilizing 3D printing to produce more efficient structural shape can improve specific tensile and flexural properties of PLA composite and these properties are increased by post tensioning. Flax gives superior tensile properties as compared to jute. Increasing the value 116% and 62% for tensile and stiffness-to-weight respectively, and 12% and 10% for flexural strength and rigidity-to-weigh respectively compared to solid unreinforced PLA.

Ferreira et.al [13] studied mechanical characterization of materials produced by 3D printing based on fused filament fabrication. The material chose for this study were polylactic acid (PLA) and a PLA reinforced with short carbon fibbers in a weight fraction of 15% (PLA+CF). Only unidirectional or specially oriented specimens were used. The result of this research was in the microstructure of PLA+CF, the short carbon fibers stayed highly oriented with the material deposition direction in FFF specimens and length of the fiber, explains differences in material properties. The PLA matrix carried out the majority of the stresses at the failure load level in both PLA and PLA+CF. Tensile modulus and shear modulus were also increased by short fiber respectively 1.25 and 1.16 times unreinforced PLA. Enhancement in Mechanical, thermal and electrical properties of thermoplastics polymer [24-26] as well as thermosetting polymer using nanofiller was studied by various researchers [27-29].

Table 1: Summary of Literature Review

SI No	Material	Concentration	Properties Enhancement		References
			Mechanical	Thermal	
1	PLA, CF	Modified CFR-PLA	TS=13.8% FS=13.8% SM=351%	-	Li et.al (2016)
2	Nylon,CF, GF, Kevlar fiber	CR-CF,GF, Kevlar fiber	TS=630% FS=500%	-	Diskson et.al (2016)
3	PLA, Graphene,	0.2% of Graphene	TS=47% SM=17% EAUF=12%	-	Greeley et.al

Table 1 : Contd.,

	MWCNT	0.1% of MWCNT	TS=41% SM=16% EAUF=9%		(2016)
4	PLA, CF, Jute fiber	CF-CR	TM=599% TS=435%	-	Matsuzaki et.al
		Jute fiber CR	TM=157% TS=134%	-	(2016)
5	PLA, Coir fiber	5-30%of coir fiber	TM=25.6% FM=13.4%	Degradation temp=332^{0}c	Dong et.al (2014)
6	Polyether ether ketone, CF	CF-CR	TS=280% EM=350% CS=290%	-	Chumaeskii et.al (2016)
7	ABS, CF	5% CF	FS=11.82% FM=16.82% FT=21.86% YM=22.5%	-	Ning et.al (2015)
8	ABS, CF	CF-CR	TS=115% TM=700%	-	Tekinalp et.al (2014)
9	PLA, Flax, Jute	Flax-CR	TS=116% FS=12%	-	Hinchcliffe et.al (2016)
10	PLA, CF	15% CF	TM=125% SM=116%	-	Ferreria et.al (2017)

[KEY: PLA-Polylactic Acid, CF- Carbon Fiber, CFR-PLA-Carbon Fiber Reinforced Polylactic Acid, TS-Tensile Strength, FS-Flexural Strength, SM-Shear Module, CR-Continuous Reinforcement, GF- Glass Fiber, MWCNT- Multi walled carbon nanotubes, EAUF-Energy Absorption Upon Facture, TM-Tensile Module, EM-Elasticity Modulus, CM-Compression Strength, ABS-Acrylonitrile Butadiene Styrene, RA- Raster Angle, IS-Infill Speed, NT-Nozzle Temperature, LT-Layer Thickness, FM- Flexural Modulus, FT- Flexural Toughness,, YM- Young's Modulus, NT-Nozzle Temperature,]

PROCEDURE

Figure 2: Fabrication and Testing Processes [9]

The entire fabricating process of thermoplastic matrix CFRP composites is shown in Figure 2. The raw materials used in this paper were virgin PLA thermoplastic pellets and carbon fiber powders (Zoltek Companies Inc., St. Louis, MO,

USA). The carbon fiber powder has two different average carbon fiber lengths, 150 mm (Panex 30) and 100 mm (panels 35), with a common fiber diameter of 7.2 mm. The pellets and carbon fiber powders were mixed in a blender with different carbon fiber contents. The plastic extruder (EB-1, Extrusion Bot Co. Chandler, AZ, USA) was used to fabricate the carbon fiber filled filaments. During the extrusion processes, extrusion temperature, filament yield speed, and nozzle diameter were set at 220^0C, 2 m/min, and 2.85 mm, respectively [14-17].The filaments could be cut into small pieces and referred in the extruder for the second extrusion to make them with high bulk density, which led to more consistent flow rates and fusion on each layer. During such process, filaments with more homogeneous distribution of carbon fibers could be obtained, thereby improving the FDM fabrication process and parts performance [18-20].The FDM 3D printer was used to fabricate CFRP composite parts. The nozzle diameter of the FDM unit was 0.35 mm and nozzle temperature was set at 230 ^{0}C during FDM process. Printing velocity was set at 1.2 m/min for the first layer and maintained at 1.5 m/min for the rest layers. 14 layers were printed with each layer thickness of 0.2 mm. The infill pattern deposition directions for different layers were 45 and 135, alternately. The infill density was set at 100% [20-23].

SUMMARY

Effect of Orientation

The orientation of printing can affect the strength and ductility of the printed object. The raster angle of [0, 90] exhibited significantly larger tensile strength, Young's modulus, and yield strength than raster angle of [45, 45]. Since tensile load was more effectively transferred from outside to carbon fibers by matrix, as indicated from the fracture interfaces of CFRP composite parts built at [0, 90] raster angle.

Effect of Carbon Fiber Reinforcement

The reinforcement of carbon fiber into the thermoplastic can increase mechanical and thermo mechanical properties. The carbon fiber percentage affects the tensile strength and other properties of thermoplastic. The percentage of carbon fiber increases, then brittleness of thermoplastic composite increases and toughness decreases. After increasing the content of carbon fiber into thermoplastic composite, Porosity became the severest. We need to find out the optimized percentage of carbon fiber, which gives superior mechanical and thermo mechanical properties.

Other Effects

Infill speed of 25 mm/s led to the largest mean values of all tensile properties, which would decrease with increase in infill speed due to less interaction and lower interfolding between contiguous raster. All tensile properties were first increased and then decreased with an inflection point at the nozzle temperature of 220^0C. Tensile strength, the Young's modulus, and yield strength had the largest mean values when layer thickness was 0.15 mm, because tightly coalesced inter layers generated a great interfolding strength.

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